

Food benefit and climate warming potential of nitrogen fertilizer uses in China

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Abstract

Chemical nitrogen (N) fertilizer has long been used to help meet the increasing food demands in China, the top N fertilizer consumer in the world. Growing concerns have been raised on the impacts of N fertilizer uses on food security and climate change, which is lack of quantification. Here we use a carbon–nitrogen (C–N) coupled ecosystem model, to quantify the food benefit and climate consequence of agronomic N addition in China over the six decades from 1949 to 2008. Results show that N fertilizer-induced crop yield and soil C sequestration had reached their peaks, while nitrous oxide (N₂O) emission continued rising as N was added. Since the early 2000s, stimulation of excessive N fertilizer uses to global climate warming through N₂O emission was estimated to outweigh their climate benefit in increasing CO₂ uptake. The net warming effect of N fertilizer uses, mainly centered in the North China Plain and the middle and lower reaches of Yangtze River Basin, with N₂O emission completely counteracting or even exceeding, by more than a factor of 2, the CO₂ sink. If we reduced the current N fertilizer level by 60% in ‘over-fertilized’ areas, N₂O emission would substantially decrease without significantly influencing crop yield and soil C sequestration.

Keywords: China, crop yield, CO₂ uptake, N₂O emission, nitrogen fertilizer

 Online supplementary data available from stacks.iop.org/ERL/7/044020/mmedia



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1. Introduction

To meet increasing food demands for feeding 22% of the world's population, China has used chemical nitrogen (N) fertilizer for more than 50 years as one of the most important

agronomic practices to stimulate crop production (Huang *et al* 2007, Galloway *et al* 2008, Vitousek *et al* 2009). During 2007–8, China ranked as the top consumer of N fertilizer, accounting for 32% of global N consumption (Heffer 2009). Per-hectare anthropogenic N additions in many fields of China, especially for typical double-, triple-cropping systems, surpassed those in the United States and Northern Europe (Ju *et al* 2009, Vitousek *et al* 2009).

Numerous field-based studies have proved that excessive N fertilizer application would reduce air and water quality, rather than further stimulate crop yield (Tilman *et al* 2002, Yan *et al* 2010, Sutton *et al* 2011). Besides, N fertilization has the potential to affect the climate system in two important ways. On the one hand, it can stimulate carbon storage in soils associated with increased plant production, and thereby reduce the atmosphere's carbon dioxide (CO₂) content (Melillo *et al* 2010, Tian *et al* 2011a). On the other hand, it can lead to the increased production of nitrous oxide (N₂O), a more potent greenhouse gas (GHG) than CO₂ (Liu and Greaver 2009, Zaehle *et al* 2011). A recent study (Lu *et al* 2009) showed that N fertilizer uses were estimated to sequester 5.96 Tg C yr⁻¹ (1 Tg = 10¹² g) in China's cropland and that the potential C sequestration rate may reach up to 12.1 Tg C yr⁻¹, a significant 'carbon benefit'. But some scientists cast doubt on this 'carbon benefit', arguing a complete analysis of the benefit must consider N₂O emission induced by N fertilizer application (Huang and Tang 2010, Schlesinger 2010). The concurrent effects of N fertilizer application on crop yield, soil C sequestration and biogenic N₂O emissions across the entire nation are not well studied. The inherent complexity of this issue requires a systems approach that is capable of addressing non-linear and interactive ecosystem processes in agricultural land.

In this study, we simultaneously estimated changes in the yields of major crops (maize, rice, spring wheat, winter wheat, soybean, barley and others) and the net fluxes of CO₂ and N₂O induced by N fertilizer uses across China's cropland during 1949–2008, by using a C–N coupled, processes-based ecosystem model, the Dynamic Land Ecosystem Model (DLEM, Tian *et al* 2011a, 2011b). The model simulations were driven by spatially-explicit data on N fertilizer uses and other environmental factors such as climate, atmospheric CO₂, tropospheric O₃, N deposition, land use and land cover change. Besides the historical model simulation, we set up several additional experiments to examine how crop yield, soil C sequestration, and net balance of CO₂ and N₂O would respond to four different levels of N fertilizer reduction.

2. Methods

2.1. Data and model

We developed historical gridded data sets to characterize changes in N fertilizer application and other environmental factors, including climate, atmospheric CO₂ concentration, O₃ pollution, N deposition, land use and cover patterns, in China's terrestrial ecosystems with a spatial resolution of

10 km × 10 km during 1900–2008. Historical N fertilizer application data were retrieved from the county-level census data during 1981–2008 and the provincial tabular data during 1950–2008 shown in China Statistical Yearbook (National Bureau of Statistics, NBS, www.stats.gov.cn/). We counted 30% of compound fertilizer as chemical N input. N fertilizer applied on agricultural land averaged 21.11 g N m⁻² yr⁻¹ in 2008, increasing by 4 g N m⁻² yr⁻¹ per decade since 1950. The highest N fertilizer uses occurred in some areas of the North China Plain for double-cropping systems and lower reaches of the Yangtze River for triple-cropping systems (figure 1). The detailed information on other input drivers can be found in our published papers (Tian *et al* 2011a, 2011b, Ren *et al* 2011, Lu *et al* 2012). These input drivers were used to force the global C–N coupled ecosystem model, the DLEM, to examine how N fertilizer uses in China's cropland have affected crop yield, soil C sequestration, and net fluxes of two major greenhouse gases (CO₂ and N₂O) since 1949. The DLEM model has been well calibrated and intensively validated against various field observations from the Chinese Ecological Research Network (CERN), and other long-term N fertilization experiments (Tian *et al* 2011a, 2011b, Ren *et al* 2011, Lu *et al* 2012). For this study, we adopted global warming potential (GWP) to calculate the time-integrated radiative forcing of 1 kg greenhouse gas emission relative to that of 1 kg CO₂ (Forster *et al* 2007). According to the Fourth IPCC Report, N₂O has a 298 times higher radiative forcing than CO₂ at a 100 yr time horizon. Our study focused on the period 1949–2008, since chemical fertilizer uses were assumed to be 0 in China before 1949 due to the lack of long-term records.

2.2. Simulation experiments

We set up a series of model simulation experiments to distinguish the impacts of N fertilizer application in agricultural land: (1) all combined experiment, in which all the driving factors change over the period 1900–2008. (2) Combined without N fertilization change, with no application of chemical N fertilizer while other factors change throughout the study period. The difference between these two experiments indicated the effects of N fertilizer application and its interaction with other environmental changes.

In order to examine the modeled responses of crop yield, soil organic carbon (SOC) storage change and GHG balance to better N management practices, we conducted sensitivity analysis by setting up five additional simulation experiments driven by four N fertilizer reduction scenarios and one control scenario (no N fertilizer application change since 1900) spanning another 20 yr after 2008 to capture the legacy effect of N fertilizer use. These sensitivity simulation experiments did not include future climate scenarios. From climate change perspectives, we firstly identified areas with average N-induced GWP of CO₂ and N₂O larger than 0 during 2000–8 as 'over-fertilized' regions where the proportion of CO₂ sink offset by N₂O emission exceeds 100%. Then we assigned four levels of N fertilizer reduction in those 'over-fertilized' areas: 0% (baseline, N fertilizer use keeping

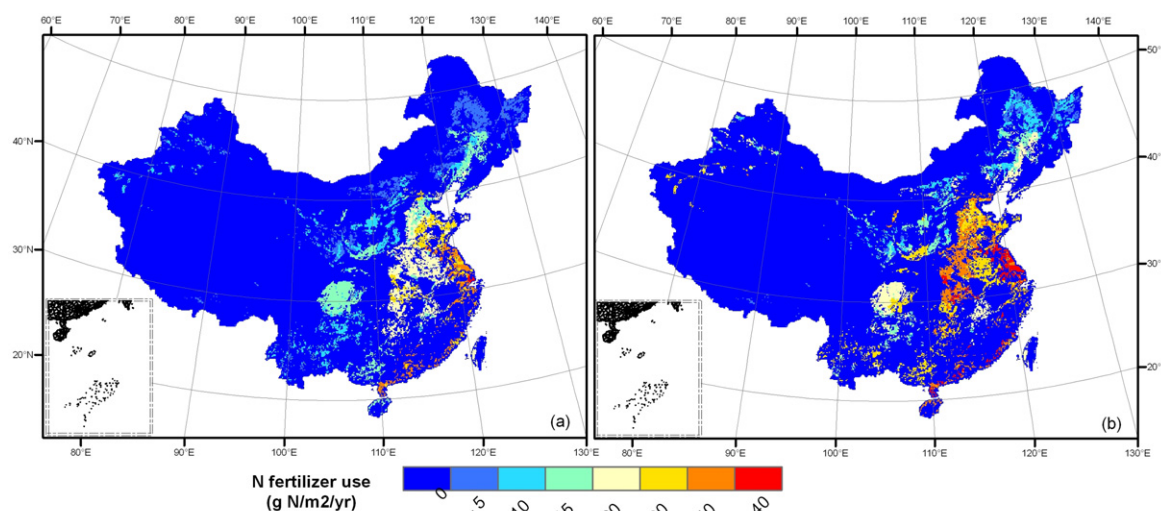


Figure 1. Spatial distribution of N fertilizer uses in China's agricultural land in 1990 (a) and 2008 (b).

constant at the current level, i.e., 2008), 20% (total amount of N fertilizer applied is equivalent to the level of late 1990s), 40% (equivalent to the level of early 1990s) and 60% (equivalent to the level of the late 1980s), while keeping N input in the remaining areas constant at the current level. Except N fertilizer application, other environmental forces were kept unchanged since 2008. The differences between the four N reduction experiments and control experiment were calculated to show the responses of China's cropland to different gradients of N fertilizer reduction. We used the N-induced changes relative to baseline simulation (0% reduction) to analyze the sensitivity of key variables to different gradients of N fertilizer reduction.

2.3. Evaluation of model performance

In this study, we validated model performance in simulating responses of crop yield, soil C sequestration and N₂O emission against the estimates from census and multiple N fertilization experiments (SBC 2000, Lu *et al* 2009, Gao *et al* 2011). The detailed data source and validation results can be found in the supplementary information (available at stacks.iop.org/ERL/7/044020/mmedia). Overall, the DLEM model is proved to perform well in simulating the dynamics in crop yield, soil C storage and GHG balance in response to N enrichment in China's cropland.

2.4. Statistical analysis

By using SPSS 20, we performed a Durbin–Watson (DW) test to examine whether serial correlation exists in N-induced CO₂ uptake and N₂O emission during 2000–8. We found negative serial correlation in N₂O emission, but the DW test is inconclusive for CO₂ uptake. After eliminating serial correlation through a Cochran–Orcutt iterative procedure, we conducted a *T* test to check if the absolute means of modified CO₂ uptake and N₂O emission are statistically different from each other regardless of their opposite direction. In order to

assess the uncertainty of model estimates, we compared the modeled soil C sequestration and N₂O emission induced by N enrichment with field experiments. RMSD (root-mean-square deviation) was adopted to indicate the difference between the model estimate and observed values in groups of upland crop and paddy fields. We then used CV (RMSD), the RMSD normalized to the mean of multi-site observed values, to calculate the weighted-average uncertainty of regional estimates for N-induced CO₂ uptake and N₂O emission.

3. Results and discussion

3.1. N fertilizer-induced crop yield and soil organic C sequestration

As simulated by DLEM, crop yield and SOC were enhanced by N fertilizer application at the annual rates of 1.8 Tg C yr⁻¹ and 1.3 Tg C yr⁻¹, respectively, during the period 1949–90. Crop yield and SOC storage reached their peaks in the early 2000s and 1990s, respectively. The N-induced soil C sequestration rate even began to decline thereafter (figure 2(a)). Although the N-induced crop yield slightly increased from 93 Tg C yr⁻¹ in the 1990s to 98 Tg C yr⁻¹ during the recent 9 yr (2000–8), we found that the relative contribution of chemical N fertilizer uses to crop yield was estimated to decrease from 53% to 49% over the past two decades. It implied that the importance of chemical N fertilizer in determining crop yield declined in recent years due to overuses of N fertilizer and increased contributions from other factors such as genetic improvement. Our findings are supported by emerging lines of evidence (Zhu and Chen 2002, Guo *et al* 2010) that partial factor productivity from fertilized N (PFP_N, calculated as the crop yield per unit nitrogen applied) declined in many fields of China in recent years, although the amount of N added as chemical fertilizer kept rising (supplementary figure S1 available at stacks.iop.org/ERL/7/044020/mmedia), implying that N fertilizer has been increasingly overused and N use efficiency in sustaining

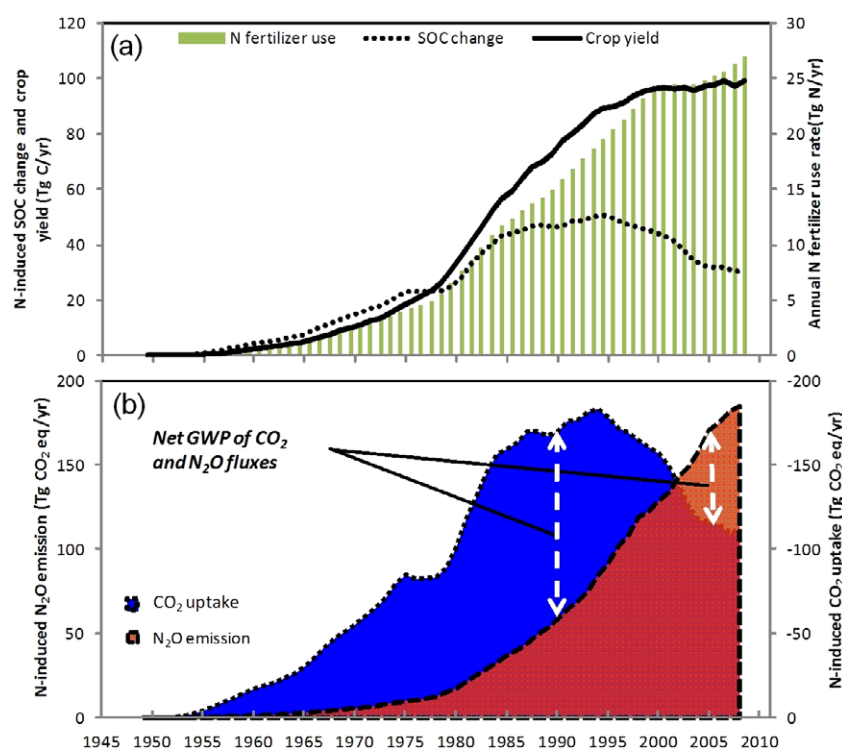


Figure 2. (a) Soil carbon sequestration, and crop yield induced by N fertilizer application in China's cropland during 1949–2008. (b) Global warming potential (GWP, unit: Tg CO₂ eq yr⁻¹) of CO₂ uptake and N₂O emission induced by N fertilizer application in China's cropland during 1949–2008. Note: GWP of CO₂ uptake is negative and surpassed N₂O emission before 2002, whereas climate change mitigation potential estimated from an increased CO₂ sink under N fertilizer application was totally offset by N₂O in recent years.

China's food security shrank. Experimental evidence also shows that N added in intensive double-cropping systems of China can be cut by 30–60% without significantly diminishing crop yield, yet reducing N loss to the environment by more than 50% (Ju *et al* 2009).

The accumulation rate of SOC due to anthropogenic N input also slowed, averaging 32 Tg C yr⁻¹ during 2000–8, compared to 48 Tg C yr⁻¹ estimated across China's cropland in the 1990s. The continuous rise in N fertilization rate might not further stimulate C accumulation in agricultural soils because crop productivity in response to N addition began to decline in large areas of China, which resulted in less C entering into the soil. In addition, long-term N fertilization experiments revealed that the more labile soil carbon fraction, including microbial and plant residues, is prone to being decomposed rather than accumulating with more available N (Neff *et al* 2002).

3.2. N fertilizer-induced GHG fluxes

Over the entire study period, N₂O emissions continued to rise as N fertilization rate increased. Direct N₂O emissions from N fertilizer uses in China was estimated to increase from 222 Gg N yr⁻¹ (1 Gg = 10⁹ g) in the 1990s to 369 Gg N yr⁻¹ throughout the recent 9 years. On a national scale, the average N₂O emission factor grew from 1.0% of fertilizer applied in the 1990s to 1.4% during 2000–8, indicating that the surplus N was increasingly released, instead of being retained in the agricultural ecosystem.

In terms of GWP, our simulations indicated that N fertilizer application acted as a small mitigator of climate warming in the early part of the study period through an N-stimulated CO₂ sink. This sink began to be offset by N₂O emissions from the 1970s onwards. Since 2002, N fertilizer-induced climate warming through N₂O emissions has exceeded the cooling effect due to CO₂ storage in China's croplands (figure 2(b)). Over the past decade (2000–8), we found that agronomic N-induced CO₂ uptake (-117.3 ± 42.5 Tg CO₂ eq yr⁻¹, mean \pm RMSD) was statistically different ($p < 0.05$) from N₂O emission (172.8 ± 43.0 Tg CO₂ eq yr⁻¹, mean \pm RMSD) even in their absolute magnitude. Up to 2008, the net GWP totaled 73 Tg CO₂ eq yr⁻¹, with N₂O emissions offsetting CO₂ uptake by 166%. CO₂ uptake and N₂O emission showed an even larger statistical difference ($p < 0.001$) after removing serial correlations.

Climate consequences of N fertilizer application in terms of GHG balance showed large spatial variability (figure 3). The largest CO₂ sink and N₂O source both occurred in the North China Plain and the middle and lower reaches of Yangtze River Basin, where typical double- and triple-cropping systems have been used and high-level N fertilizer has been applied (figures 3(a)–(d)). Compared to the 1990s, the largest CO₂ sink shown in the mid-mainland of China began to diminish, while the maximum N₂O source continued to expand over the recent 9 years. Our study shows that the net warming effect associated with N fertilizer uses mainly centered in intensively managed crop systems, with N₂O emission completely counteracting or even exceeding,

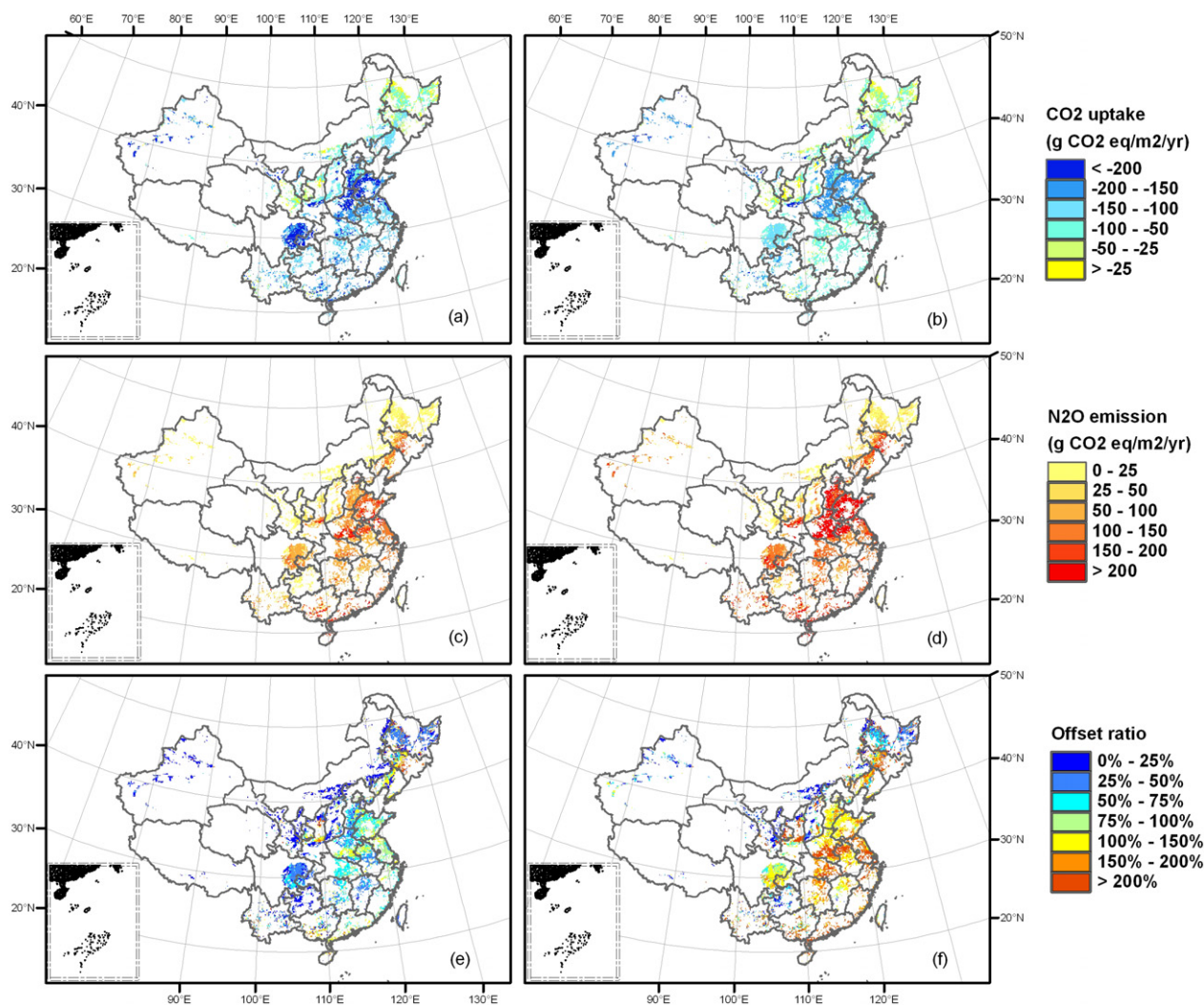


Figure 3. Global warming potential of (a), (b) CO₂, and (c), (d) N₂O, and (e), (f) offset ratio of N₂O emission to CO₂ sink induced by N fertilizer application in China's cropland during the 1990s (left panel) and the period 2000–8 (right panel).

by more than a factor of 2, the CO₂ sink during the recent 9 years (color yellow to orange in figure 3(f)). Only a small portion of China's cropland still played a mitigating role for the local and global climate system, with CO₂ uptake largely offset by the concurrently released N₂O from soils (color blue to green in figure 3(f)).

3.3. Sensitivity analysis of N fertilizer reductions

We assumed that N fertilizer uses in 'over-fertilized' areas of China (defined as offset ratio larger than 100% in figure 3(f)) would be reduced by 0% (baseline, continue applying N fertilizer in current rate), 20%, 40% and 60%, and used these four N fertilizer reduction levels to extend the model simulations for another 20 years. The 'what-if' experiments are able to reveal the likely patterns of crop yield, soil C storage and net GWP of CO₂ and N₂O fluxes in response to different N management strategies. Amazingly, our simulation showed that both crop yield and soil C sequestration induced by N fertilizer uses would decrease, but not change much with N fertilizer reductions compared to those driven by

current N fertilizer use rate. For example, 60% of N reduction would lead to an N-induced crop yield decrease of 1.88 Tg C yr⁻¹ or 2%, compared to the experiment continuing fertilizer application at the current rate. However, direct agricultural N₂O emission would significantly decrease along with less N fertilizer inputs (table 1). Compared to the baseline, N-induced N₂O emission would decrease by 99 Tg CO₂ eq yr⁻¹, or 49.8%, with N fertilizer reduced by 60% of the current level in 'over-fertilized' areas. We also found that the amount of N leached out of the ecosystem largely decreased with N fertilizer reductions while plant N uptake remained with no significant changes. This implied that in 'over-fertilized' areas N fertilizer reduction as high as 60% would substantially decrease the loss of excessive N, alleviate air and water pollution, while not apparently suppressing crop yield.

With N fertilizer reduced by 40%–60%, the modeled CO₂ uptake in China's cropland showed a small decrease of 8.5%–15.8% compared to that driven by current fertilizer use rate (table 1). However, N₂O emission would largely decrease as N fertilizer use reduces. For example, as simulated by

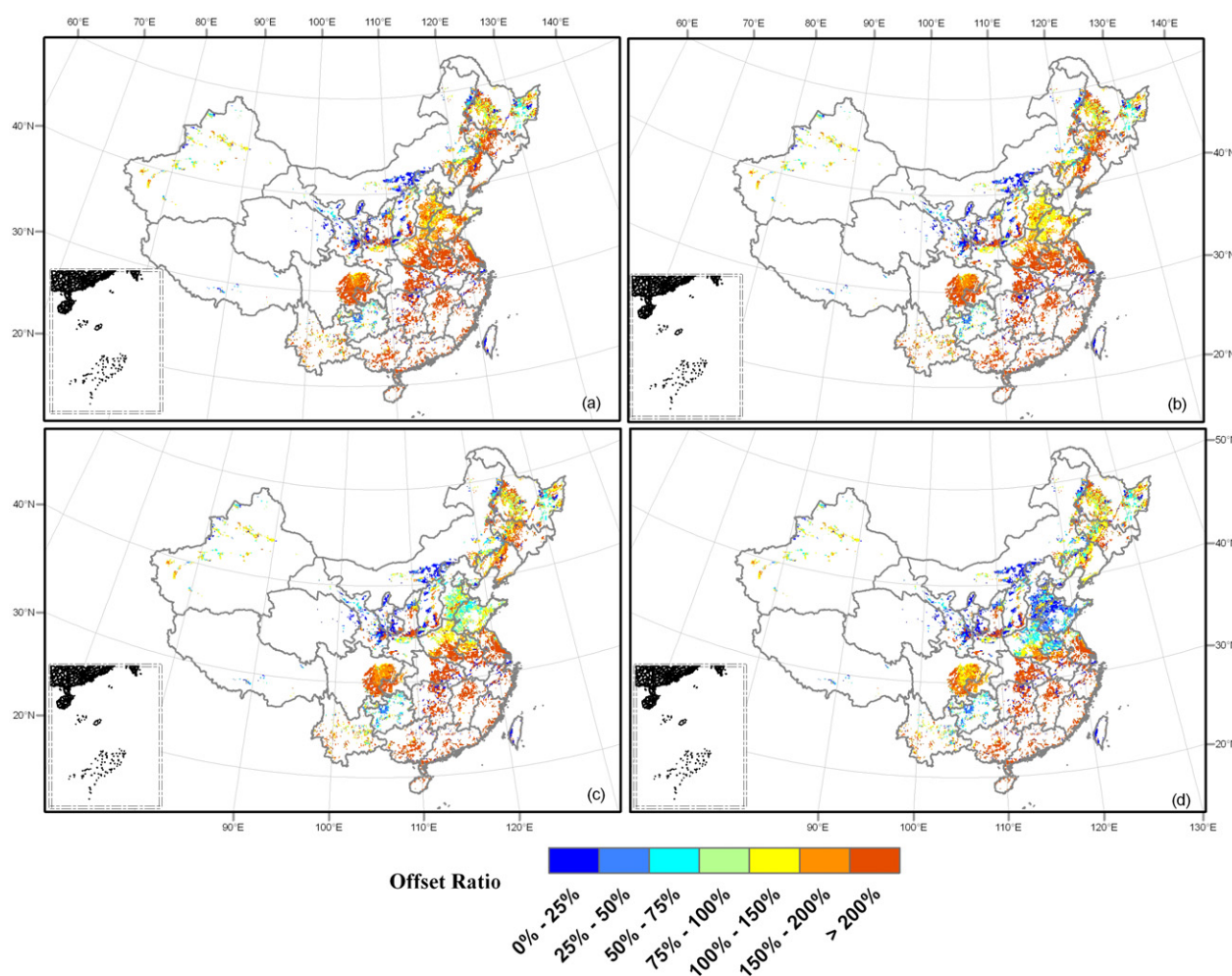


Figure 4. Offset ratio of N₂O emission to CO₂ sink induced by 4 levels of N fertilizer reduction in China's cropland: (a) N fertilizer kept constant at current level; (b) N fertilizer reduced by 20% of current level; (c) N fertilizer reduced by 40% of current level; (d) N fertilizer reduced by 60 per cent of current level in the 'over-fertilizer' areas (offset ratio ≥ 1 during 2000–8).

Table 1. Sensitivity analysis on impacts of different N reduction levels on crop yield, soil organic C (SOC) sequestration, GHG balance and leaching of N (including both dissolved inorganic N and dissolved organic N) in China's cropland. (Note: (a) the percentages shown in the table are the simulated changes in crop yield, soil C sequestration and GHG balance induced by three levels of N reduction relative to those corresponding values driven by the current (2008) N fertilizer application rate. (b) Nfer_20%, Nfer_40% and Nfer_60% stand for simulation experiments with N fertilizer use reduced by 20%, 40% and 60% of the current level in 'over-fertilized' areas, respectively.)

N reductions	N-induced changes	Yield (Tg C/yr)	SOC change (Tg C/yr)	CO ₂ uptake (Tg CO ₂ eq/yr)	N ₂ O emission (Tg CO ₂ eq/yr)	Net GWP (Tg CO ₂ eq/yr)	N leaching (Tg N/yr)
Nfer_20%	change	−0.88	−0.89	−3.29	−22.38	−19.08	−3.58
	change perc	−0.9%	−3.3%	−3.3%	−11.2%	−19.2%	−21.60%
Nfer_40%	change	−1.88	−2.31	−8.56	−56.25	−47.70	−6.82
	change perc	−2.0%	−8.5%	−8.5%	−28.2%	−48.0%	−41.10%
Nfer_60%	change	−1.88	−4.26	−15.82	−99.38	−83.55	−9.70
	change perc	−2.0%	−15.6%	−15.8%	−49.8%	−84.1%	−58.40%

DLEM, the net GWP values would decrease by 84%, and the CO₂ sink offset ratio would be lowered to 119% with 60% N fertilizer reduction. Therefore, if we reduce N fertilizer uses by ~60% in 'over-fertilized' areas, China's cropland would act as a small to neutral climate heater while keeping crop yield relatively stable.

With N fertilizer use reduction, the N-induced climate warming area in China's cropland would significantly shrink.

The decreased offset ratio primarily occurred in the North China Plain, across which large areas of cropland would turn to a mitigator of climate warming with N fertilizer use reduced by 40%–60% (figure 4). However, such a reduction would not completely change the climatic role of cropland in the southeastern part. This might be related to the following facts: (1) typical double- and triple-cropping systems distributed in this area were characterized by intensive or excessive

agronomic N inputs; (2) other N sources such as higher N deposition and mineralized N due to faster turnover in this region provide a large amount of soil available N, which is the major substrate of N₂O production.

3.4. Uncertainty and research needs

While using a systems approach to simultaneously examine N fertilizer impact on crop yield, soil C storage and GHG balance, our estimated responses may have some uncertainties for several reasons. First, we ignored growth limitations from other nutrients such as potassium (K) and phosphorus (P), and made the assumption of an optimized irrigation strategy without water logging (Ren *et al* 2011) which might, to a small degree, have led us to overestimate the responses of crop yield to anthropogenic N additions. Second, we included maize, rice, spring wheat, winter wheat, soybean, barley and other crops in China to represent both upland and paddy fields, and then assumed N fertilizer use per unit harvest area of grain crops in each county was the same as that of cash crops such as vegetable and fruits. The harvest area of cash crops accounted for more than one fifth of China's arable and permanent crop area in 2005, with N fertilizer consumption over 30% of the national total (Heffer 2009). This simplification might, on the one hand, cause our underestimation on the decline of N-induced crop yield and the increase of N₂O emission, since cash crops tend to be more fertilizer intensive, and less effective in using N than grain crops. On the other hand, our simulation might overestimate N₂O emission, since implementation of a soil testing and fertilizer recommendation (STFR) program in some areas of China over 2001–8 was shown to reduce chemical N fertilizer uses and consequently decrease N₂O emission from wheat, rice and maize crops (Sun and Huang 2012). Third, our optimized water management (mid-season drainage) assumption would partly overestimate N₂O emission, as dry–wet alteration in paddy fields was proved to stimulate nitrification and denitrification processes, and therefore favor N₂O emission (Zou *et al* 2010). However, the resulting bias would not radically change our major conclusion.

This study does not consider CO₂ emission from N fertilizer production, transport and application (Huang and Tang 2010, Schlesinger 2010). Indirect N₂O emissions derived from re-deposition of volatilized N and N leached to downstream aquatic ecosystems (Zaehle *et al* 2011) are excluded here. If considering these two components, the stimulating effect of N fertilizer uses on climate warming would be higher than that estimated in this study. In addition to stimulating climate warming, excessive N fertilizer uses contributed to increasing the potential N pollution and eutrophication in downstream aquatic ecosystems (table 1). Taking both atmospheric and aquatic environment costs into account is urgently needed for assessing the impacts of agronomic N input in future studies.

4. Conclusion

Past research efforts have led to a growing recognition that N fertilizer is commonly overused in China's agricultural

production and has widely caused environmental problems. However, few studies have considered the climate consequences of excessive N fertilizer application in China. From our study we draw the following conclusions: (1) crop yield in China was substantially boosted by chemical N fertilizer uses over the past decades, but it was shown to barely further increase with surplus N input in recent years; (2) SOC accumulation induced by N added in cropland reached its peak in the 1990s and has since declined; (3) overuse of chemical N fertilizer in China has led to an expanding warming effect, with direct N₂O emission offsetting the soil carbon sink by 166% in 2008; (4) the largest net sources of greenhouse gases associated with agronomic N addition have occurred in the North China Plain and in the middle and lower reaches of the Yangtze River Basin, where intensively managed crop systems are located; (5) if we reduce N fertilizer use by 60% in the 'over-fertilized' region, N-induced crop yield and SOC sequestration would slightly decrease, but direct N₂O emission would substantially decrease, and China's cropland would act as a small to neutral climate heater while keeping crop yield relatively stable; (6) The most apparent mitigation of climate warming due to N fertilizer reduction practices would occur in the North China Plain. Our research suggests that enhancing N use efficiency instead of increasing N inputs in the future would be more effective to sustain China's food security and cropland soil C sequestration, and diminish the climate warming and water pollution aggravated by anthropogenic N enrichment.

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References

- Forster P *et al* 2007 Changes in atmospheric constituents and in radiative forcing *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* ed S Solomon, D Qin, M Manning and Z Chen (Cambridge: Cambridge University Press) pp 129–234
- Galloway J N *et al* 2008 The environmental reach of Asia *Annu. Rev. Environ. Resour.* **33** 461–81
- Gao B, Ju X, Zhang Q, Christle P and Zhang F 2011 New estimates of direct N₂O emissions from Chinese croplands from 1980 to 2007 using localized emission factors *Biogeosciences* **8** 3011–24
- Guo J H *et al* 2010 Significant acidification in major Chinese croplands *Science* **327** 1008–10
- Heffer P 2009 *Assessment of Fertilizer Use by Crop at the Global Level 2006/07–2007/08* (Paris: International Fertilizer Industry Association) (www.fertilizer.org)
- Huang Y and Tang Y 2010 An estimate of greenhouse gas (N₂O and CO₂) mitigation potential under various scenarios of nitrogen use efficiency in Chinese croplands *Glob. Change Biol.* **16** 2958–70

- Huang Y, Zhang W, Sun W and Zheng X 2007 Net primary production of Chinese croplands from 1950 to 1999 *Ecol. Appl.* **17** 692–701
- Ju X T et al 2009 Reducing environmental risk by improving N management in intensive Chinese agricultural systems *Proc. Natl Acad. Sci. USA* **106** 3041–6
- Liu L and Greaver T L 2009 A review of nitrogen enrichment effects on three biogenic GHG: the CO₂ sink may be largely offset by stimulated N₂O and CH₄ emission *Ecol. Lett.* **12** 1103–17
- Lu C Q et al 2012 Effects of nitrogen deposition on China's terrestrial carbon uptake in the context of multi-factor environmental changes *Ecol. Appl.* **22** 53–75
- Lu F et al 2009 Soil carbon sequestrations by nitrogen fertilizer application, straw return and no-tillage in China's cropland *Glob. Change Biol.* **15** 281–305
- Melillo J M, Kicklighter D W, Tian H Q and Butler S 2010 Fertilizing change: carbon–nitrogen interactions and carbon storage in land ecosystems *Handbook of Climate Change and Agroecosystems: Impacts, Adaptation, and Mitigation* ed D Hillel and C Rosenzweig (London: Imperial College Press) pp 21–36
- Neff J C et al 2002 Variable effects of nitrogen additions on the stability and turnover of organic carbon *Nature* **419** 915–7
- Ren W et al 2011 Spatial and temporal patterns of CO₂ and CH₄ fluxes in China's croplands in response to multifactor environmental changes *Tellus B* **63** 222–40
- SBC (Statistics Bureau of China) 2000 *Agricultural Database from 1950 to 1999* (Beijing: China Statistics Press) (in Chinese)
- Schlesinger W H 2010 On fertilizer-induced soil carbon sequestration in China's croplands *Glob. Change Biol.* **16** 849–50
- Sun W and Huang Y 2012 Synthetic fertilizer management for China's cereal crops has reduced N₂O emissions since the early 2000s *Environ. Pollut.* **160** 24–7
- Sutton M A et al 2011 Too much of a good thing *Nature* **472** 159–61
- Tian H Q et al 2011a China's terrestrial carbon balance: Contributions from multiple global change factors *Glob. Biogeochem. Cycles* **25** GB1007
- Tian H Q et al 2011b Net exchanges of CO₂, CH₄, and N₂O between China's terrestrial ecosystems and the atmosphere and their contributions to global climate warming *J. Geophys. Res.* **116** G02011
- Tilman D, Cassman K G, Matson P A, Naylor R and Polasky S 2002 Agricultural sustainability and intensive production practices *Nature* **418** 671–7
- Vitousek P M et al 2009 Nutrient imbalance in agriculture development *Science* **324** 1519–20
- Yan W, Mayorga E, Li X, Seitzinger S P and Bouwman A F 2010 Increasing anthropogenic nitrogen inputs and riverine DIN exports from the Changjiang River basin under changing human pressures *Glob. Biogeochem. Cycles* **24** GB0A06
- Zaehle S, Ciais P, Friend A D and Prieur V 2011 Carbon benefits of anthropogenic reactive nitrogen offset by nitrous oxide emissions *Nature Geosci.* **4** 601–5
- Zhu Z L and Chen D L 2002 Nitrogen fertilizer use in China—contribution to food production, impacts on the environment and best management strategies *Nutri. Cycling Agroecosyst.* **63** 117–27
- Zou J, Lu Y and Huang Y 2010 Estimates of synthetic fertilizer N-induced direct nitrous oxide emission from Chinese croplands during 1980–2000 *Environ. Pollut.* **158** 631–5